Emission of light mesons directly from the surface of quark-gluon plasma.

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On the basis of hydrodynamic model of evolution we consider emission of lightest $(\pi, K, \eta, \rho, \omega, K^*)$ mesons directly from the surface of quark-gluon plasma, created in the heavy ion collision, with accounting of their absorption by surrounding hadronic gas. We evaluate upper and lower limits on yields of these direct mesons in Pb+Pb collisions at SpS, RHIC and LHC energies, and find, that even in the case of the lowest yield, direct K, η and heavier mesons dominate over freeze-out ones at soft p_t ($p_t \leq 0.5\,GeV/c$). This leads to enhancement of the low p_t production of these mesons which hardly can be explained within pure hadronic gas scenario, and can be considered as quark-gluon plasma signature.

25.75.-q,12.38.Mh,25.75.Dw,24.10.Nz

As a rule, considering heavy ion collision with QGP creation, one assumes, that hadrons, produced on plasma surface, suffer numerous rescatterings in the surrounding hadronic gas, so that final hadrons do not carry direct information about plasma. In this letter we show, that this widely accepted opinion is not quite right for the case of finite systems, created in heavy ion collisions. Because of comparability of free path lengths of hadrons in the hadronic gas with sizes of the region, occupied by hot matter, significant number of hadrons, created on the surface of quark-gluon plasma can pass through the surrounding hadronic gas without rescattering. Such kind of final state hadrons we call *direct* hadrons below. In contrast to the usually considered *freeze-out* hadrons, originated due to evaporation from the hadronic gas or its freeze-out, direct hadrons carry immediate information about the plasma surface. The goal of this letter is to show, that the yield of direct mesons is not negligible small, and moreover, there is kinematic region, where direct hadrons dominate over freeze-out ones.

The rather obvious itself fact, that final hadrons are emitted not from thin freeze-out hypersurface, but from the whole volume, occupied by hadronic gas, was noted several times within different models of AA collisions: within quark-gluon string model [1], within the model, combining hydrodynamic description of evolution of QGP and relativistic quantum molecular dynamics for hadronic gas [2], within similar to our approach, used in papers [3] for evaluation of hadronic emission from the depth of hadronic gas. Nevertheless, until our paper [4], there were no attempts to separate direct hadrons from QGP surface from ones from hadronic gas. Surely, one can not point out hadron and tell, that it e.g. came from QGP surface, but as we will show, it is possible to find kinematic region, where hadrons from QGP surface dominate. In the paper [4] we considered S+Au collision at $200\,A\cdot GeV$ (SpS) and evaluated yields of direct and freeze-out pions. We showed that direct pions can dominate in soft p_t region, what result in enhancement of the yield of pions with low p_t. However, there are a lot of effects, such as resonance decay, absence of chemical equilibrium etc., which lead to the similar enhancement of pion spectrum, making strong physical background for direct pions. In this letter, in addition to pions, we evaluate emission of heavier direct and freeze-out mesons: K, η, ρ, ω and K^* in AA collisions at SpS, RHIC and LHC energies, and demonstrate, that for heavier mesons contribution of direct mesons is even larger than for pions while physical background is negligible.

To estimate yields of the direct mesons in heavy ion collision we use the following model. Hot matter, created in the very beginning of collision, evolves hydrodynamically. On the background of this evolution the direct mesons are continuously emitted from the surface of QGP as a result of flying out of quarks and gluons from the depth of quark-gluon plasma, their hadronization on the plasma surface and fly out of the direct mesons through surrounding expanding hadronic gas sometimes with rescattering. If direct meson suffers rescattering in the hadronic gas, then we assume, that it lost direct information about plasma and consider it further hydrodynamically. For freeze-out hadrons we assume thermodynamic and chemical equilibrium at freeze-out moment. More elaborated description of freeze-out of hadronic gas, such as e.g. [5], can only increase the relative yield of direct hadrons.

Probability for quark and gluon being emitted in the depth of QGP to reach its surface, and for meson to escape from hadronic gas without rescattering is determined by expression:

$$P = \exp\left\{-\int \lambda^{-1}(\varepsilon, x)\,dx\right\},$$

where integration is performed along the path of the particle in the hot matter with accounting of its evolution, and $\lambda(\varepsilon, x)$ - free path length of the particle, which depends on energy of the particle ε and local energy density at the point x. We calculate free path lengths of quark and gluon in QGP and meson in hadronic gas using equation

$$\lambda_i(\varepsilon)=\left[\frac{1}{16\,\pi^3}\frac{T}{\varepsilon\;p}\sum_j\int\limits_{(m_1+m_2)^2}^{\infty}\sqrt{s^2-2\,s\,(m_1^2+m_2^2)+(m_1^2-m_2^2)^2}\,\sigma_{ij}(s)\;\ln\left(\frac{1-\exp(-a_+)}{1-\exp(-a_-)}\right)\,ds\right]^{-1},$$

$$a_\pm=\frac{\varepsilon(s-m_1^2-m_2^2)\pm\sqrt{(\varepsilon^2-m_1^2)(s^2-2\,s\,(m_1^2+m_2^2)+(m_1^2-m_2^2)^2)}}{2\,m_1^2\,T},$$

where $\sigma_{ij}(s)$ – total cross-section of interaction of i and j particles, m_1 and m_2 – mass of projectile and target particles correspondingly, T – temperature, and sum is taken over all possible two-particle reactions. Evaluating free path lengths of hadrons in hadronic gas we take into account only rescatterings on pions. In the case of the free path length of pions we use experimental cross-sections of $\pi\pi$ scattering (see [4]), while for $K, \eta, ...$ we assume $\sigma=\sigma_{\pi^+\pi^+}\sim 10\,mb$ plus contributions from excitation of resonances. One could expect, that presence of nucleons in the hadronic gas results in significant reduction of the free path length of the pion with respect to pure pionic gas (due to excitation of Δ resonances). However, below we concentrate on the midrapidity region, where net baryon density is small, and for reasonable values of barionic chemical potential $\mu\leq 300\,MeV$ and temperatures below $\sim 200\,MeV$, we find, that contribution of nucleons into free path length of pions is negligible.

Emission rate (the number of particles, emitted from unit volume per unit time) of quarks and gluons from QGP we find from the condition, that infinitely thick layer of QGP emits quarks and gluons in accordance with Stephan-Boltsman formula. So we find:

$$\varepsilon\frac{d^7R_i}{d^3p\,d^4x}=\frac{d_i}{\lambda_i(\varepsilon)}\frac{\varepsilon}{(\exp(\varepsilon/T)\pm 1)}.$$

where d_i – degeneracy, λ_i – free path length of the particle, T – temperature.

In this letter we interest in p_t distributions at midrapidity region, therefore we restrict ourselves by Bjorken 2+1 hydrodynamics with transverse expansion, which provides good description of evolution of hot matter at this region.

As far as it is not possible to describe consistently hadronization of quarks and gluons on the plasma surface, we estimate upper and lower limits on the yields of direct hadrons, by use of two models of hadronization – 'creation' model, giving the lower limit and 'pull in' model, used in the paper [4] and giving the upper limit. In both models we assume, that a quark or gluon, flown through the plasma surface, pulls tube (string) of color field. Creation of the final hadron corresponds to the breaking of the tube due to discoloring of the moving out quark or gluon. In the first model we assume, that this discoloring takes place as a result of creation of a quark-antiquark pair in the strong field of the tube. This assumption is used in the well known Lund model, and implemented in the event generator JETSET [6], where all parameters are chosen to fit the e^+e^- annihilation at $\sqrt{s}=30\,GeV$. Therefore, in the 'creation' model we extract corresponding probabilities from JETSET 7.4. In the second model we assume, that discoloring takes place as a result of 'pulling in' of soft quark or gluon with corresponding color from the pre-surface layer of QGP into the tube. Because of the large number of soft quarks and gluons in the QGP *each* moving out quark and gluon can transform into some hadron, providing its energy is larger than mass of this hadron. If several hadrons can be formed, then we take their relative yields from e^+e^- annihilation at $\sqrt{s}=30\,GeV$. The main difference between these two models is in the probability of fragmentation of soft quarks and gluons: in the 'pull in' model probability is independent on energy, while in the 'creation' model probability of creation of quark pair in strong field is proportional to $\exp(-\varepsilon^2/p_0^2)$, where ε - energy of the quark and $p_0\sim 0.5\,GeV$. Having probabilities of hadronization of quarks and gluons into hadron $R_h^{q,g}(\varepsilon_q)$, evaluated using these two models, we obtain the following hadronization function:

$$f_h^{q,g}(\varepsilon_h,\theta_h,\phi_h)=2\,R_h^{q,g}(\varepsilon_q)\frac{\delta(\phi_h-\phi_q)\,\delta(\cos\theta_h-\cos\theta_q)\,\theta(\varepsilon_q-m_h)}{\varepsilon_q\sqrt{\varepsilon_q^2-m_h^2}-m_h^2\ln\left(\varepsilon_q/m_h+\sqrt{\varepsilon_q^2-m_h^2}\Big/m_h\right)}$$

where ε,θ,ϕ energy, polar angle and azimuthal angle of initial quark (q) or gluon (g) or final hadron (h) correspondingly, and m_h – mass of the hadron. This fragmentation function is normalized to describe fragmentation of one quark or gluon to $R_h^{q,g}(\varepsilon_q)$ hadrons with energy in the range $m_h<\varepsilon_h<\varepsilon_q$.

To apply our model to central $Pb+Pb$ collisions at $158\,A\cdot GeV$ we choose initial conditions (initial temperature T_{in}, time of thermalization τ_{in} and initial radius R_{in}), QGP-hadronic gas transition temperature (T_c) and freeze-out

temperature (T_f) to reproduce experimental p_t distribution of π^0 at midrapidity [7]. So we use:

$$T_{in} = 350\,MeV,\ \tau_{in} = 0.25\,fm/c,\ R_{in} = 6.5\,fm,\ T_c = 160\,MeV,\ T_f = 140\,MeV.$$

Evaluated p_t distributions of various mesons at midrapidity for the 'pull in' and 'creation' models of hadronization of quarks and gluons are shown on the fig. 1. We do not distinguish isotopic projections of mesons, so we show distributions, averaged over all pions, kaons etc.

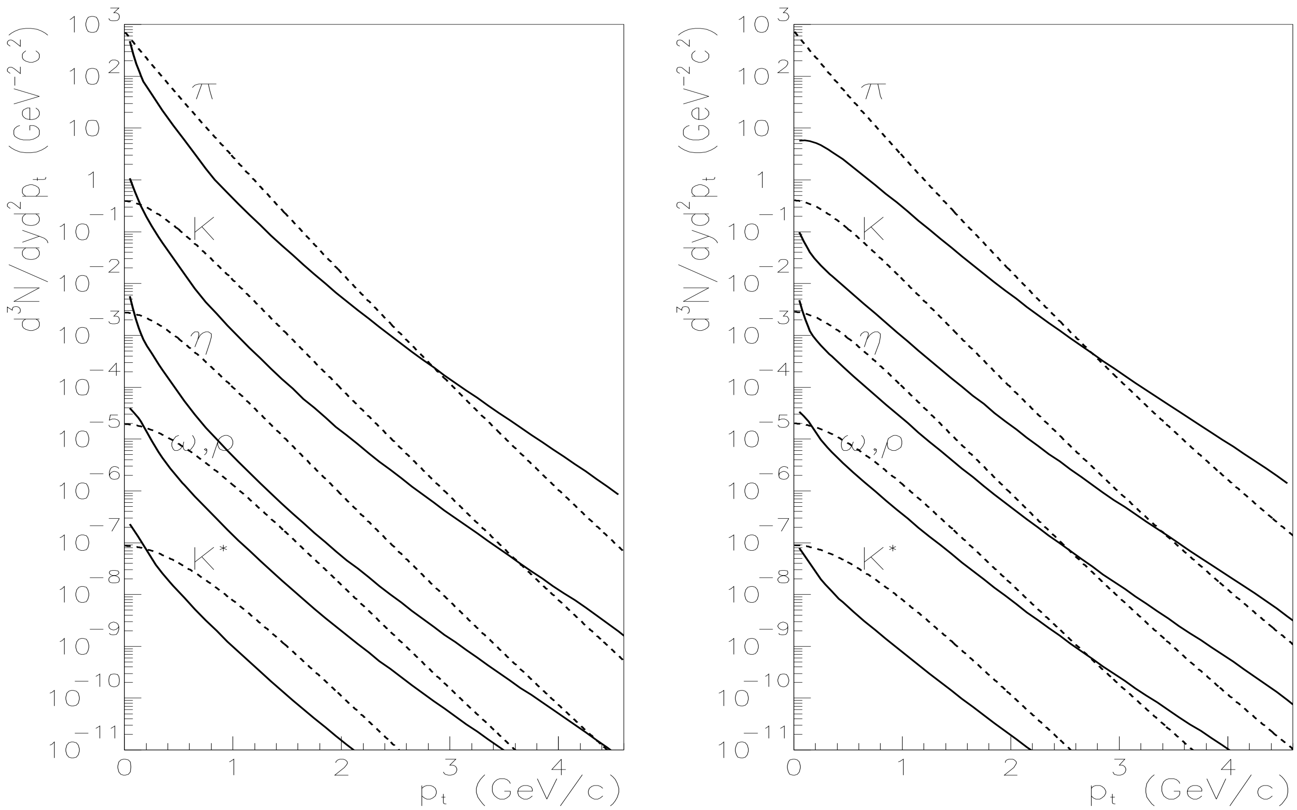

FIG. 1. Yields of direct (solid lines) and freeze-out (dotted lines) mesons in Pb+Pb collision at SpS energy within 'pull in' (left plot) and 'creation' (right plot) models of hadronization of quarks and gluons on plasma surface. Distributions of $K, \eta, ...$ are multiplied by $10^{-2}, 10^{-4}, ...$

We find, that the yield of direct mesons is comparable with the yield of freeze-out ones, see fig. 1. The contribution of direct mesons is higher within 'pull in' model, what is the consequence of higher probability of fragmentation of low energy quarks and gluons in the this model of hadronization. Nevertheless, within both models of hadronization direct η and heavier mesons dominate over freeze-out ones at soft p_t. Thus we obtain unexpected result, that direct mesons, emitted from the hottest region of the collision, dominate not only in the hard part of spectrum, but also in the soft p_t region. This takes place because quark or gluon, hadronizing on the plasma surface, spreads its energy between the direct hadron and a part of color tube, which is pulled back to plasma, what leads to non-thermal spectrum of direct hadrons.

To investigate dependence of the yields of direct mesons on the energy of collision, we evaluated these yields in the central $Pb + Pb$ collisions at $3100 + 3100\,A \cdot Gev$ (LHC). To do this we used the following initial conditions:

$$T_{in} = 1\,GeV,\ \tau_{in} = 0.15\,fm/c,\ R_{in} = 6.5\,fm.$$

what corresponds to the multiplicity at midrapidity $dN/dy \sim 10^4$, predicted by cascade models, while transition and freeze-out temperatures remains the same as for SpS. Distributions of direct and freeze-out hadrons, evaluated in this case are shown on fig. 2.

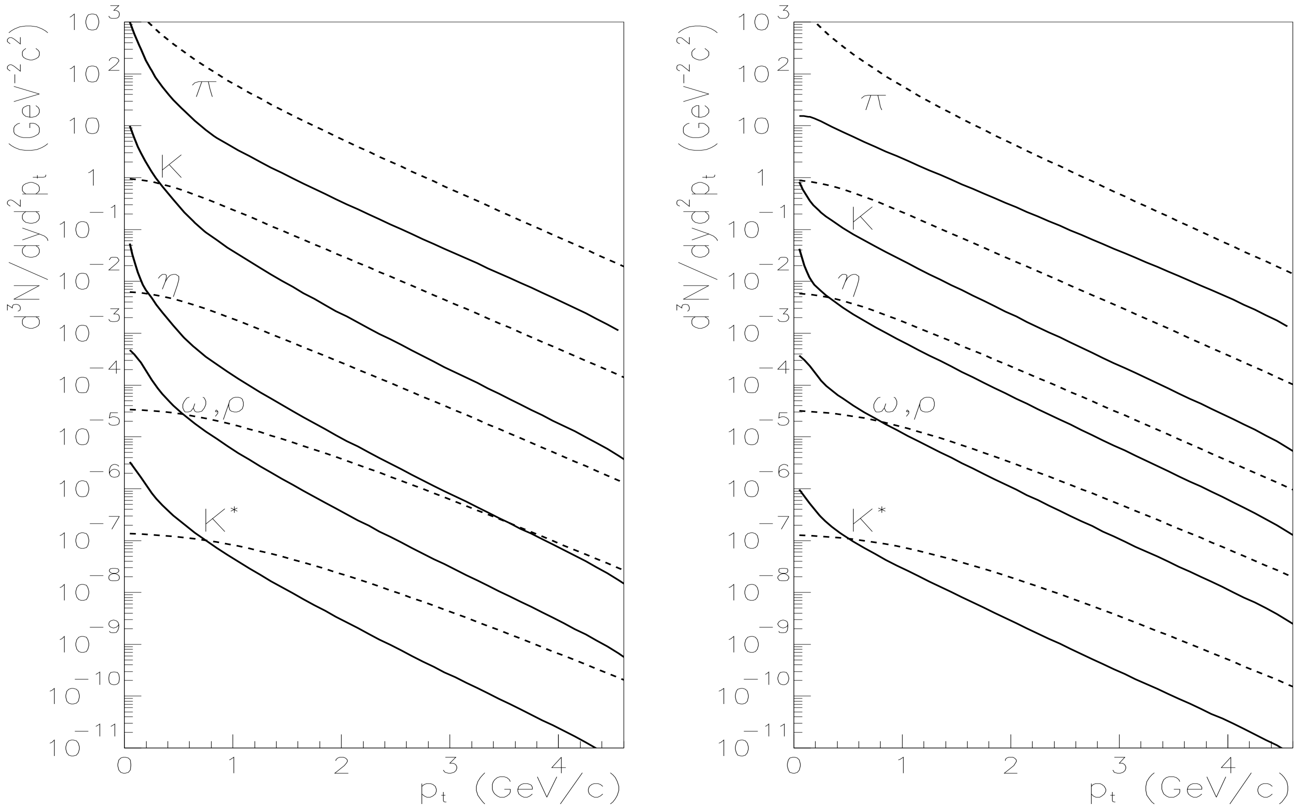

FIG. 2. Yields of direct (solid lines) and freeze-out (dotted lines) mesons in Pb+Pb collision at LHC energy within 'pull in' (left plot) and 'creation' (right plot) models of hadronization of quarks and gluons on plasma surface. Distributions of $K, \eta, ...$ are multiplied by $10^{-2}, 10^{-4}, ...$.

In contrast to SpS, direct hadrons do not dominate at hard p_t at LHC energy, because at this energy collective radial velocity of hadronic gas compensate slightly higher temperature in the pre-surface layer of QGP from which direct hadrons are emitted. In return, due to longer QGP phase direct mesons more significantly contribute to low p_t region. Again, for η and heavier mesons direct hadrons dominate at soft p_t within both models of hadronization.

For the sake of brevity we do not present here plots for RHIC energy, but the contribution of direct hadrons can be easily estimated using figs. 1 and 2 and Table 1.

We summarized the parts of direct mesons in the total meson yield, evaluated for two models of hadronization for SpS, RHIC and LHC energies on the Table 1. As one can see, the part of direct hadrons is considerable and increase with increasing of the energy of collision.

TABLE I. Part of direct mesons in the total meson yield in midrapidity region.

	SpS		RHIC		LHC	
meson	'pull in'	'creation'	'pull in'	'creation'	'pull in'	'creation'
π^0	0.31	0.04	0.27	0.04	0.12	0.03
K	0.38	0.10	0.4	0.11	0.35	0.13
η	0.25	0.31	0.27	0.35	0.21	0.37
ρ, ω	0.33	0.36	0.39	0.45	0.42	0.52
K^*	0.35	0.19	0.43	0.26	0.44	0.34

We find, that direct hadrons considerably contribute to the total hadronic yield: contributions of direct η and heavier mesons reach ~ 0.5 of the total yield. Direct mesons contribute not only to the hard part of spectrum (at SpS energies) but also at low p_t. We would like to stress, that domination of direct hadrons in the soft p_t region is not artifact of our model, but the consequence of two rather general physical requirements. First – a part of the energy of quark or gluon is lost during their hadronization. Second – there is approximate thermal equilibrium, to that extend, which is usually observed in heavy ion collisions. As for the value of this domination, it certainly depends on the details of the model: on the probability of hadronization, transparency of hadronic gas and details of evolution of the hot matter. We estimated sensitivity of the yield of direct hadrons to these parameters. In this letter we evaluated upper and lower limits for the probability of hadronization, while in the paper [4] we estimated sensitivity to variations of free path lengths and hydrodynamic parameters. As a result, we find that the yield of direct hadrons is rather stable with respect to variation of model parameters, and can not be changed considerably within reasonable models.

Contribution of direct hadrons change the shape of the meson spectrum, what can be used, in principle, as quark-gluon plasma signature. But to do this one have to answer the question: 'is it possible to find such enhancement within pure hadronic picture of the collision?'. Fortunately for us, excess of low p_t pions in AA collisions was observed experimentally long ago (see e.g. [8]) and caused active discussion of possible sources of such excess in literature. The review of proposed reasons for such excess can be found in [9]. It includes:

- Resonance decays [10], mainly Δ and N^*. This effect is very important for pions, especially at target and projectile regions, however, it brings negligibly small contribution to spectra of η and heavier mesons. The number of heavier resonances, which can decay onto mesons we consider, multiplied by branching of this decay is well below the number of direct mesons (see Table 1).

- Collective motion, as was demonstrated in [11] explained observed enhancement, but later it was shown [12], that this explanation was consequence of rather specific and unnatural freeze-out conditions, used in [11]. Within more physical hydrodynamic models radial collective expansion does not bring such contribution.

- Absence of chemical equilibrium in pion gas [13]. This effect essentially uses suppression of channels, changing the number of pions with respect to elastic scattering. In the case of heavier mesons this is not the case, so this effect does not contribute as well.

Therefore we find that excess of low p_t η and heavier mesons can not be explained within pure hadronic scenario of collision, and, possibly, can be considered as quark-gluon plasma signature.

To conclude, we consider emission of light ($\pi\, K$, η, ρ, ω, K^*) mesons directly from the surface of quark-gluon plasma in the case of its creation in nucleus-nucleus collision. These mesons are continuously emitted from the surface of QGP due to fly-out of quarks and gluons from pre-surface region, their hadronization and subsequent escape from hot matter without interactions. Direct mesons give unique opportunity to test the pre-surface layer of QGP via strongly interacting particles. We evaluated yields of direct and freeze-out mesons in SpS, RHIC and LHC energies, and find, that direct mesons considerably contribute to the total meson emission – their contributions reach ~ 0.5 of total yield. Moreover, direct hadrons dominate over freeze-out ones in the soft part of spectrum, what result in enhancement of low p_t η and heavier meson productions, what, as we have shown, can not be explained within pure hadronic gas scenario and can be considered as QGP signature. We argue, that such effect is the result of two natural assumptions: first – there is approximate thermodynamic equilibrium, that is, there is no drops of matter with extremely low temperature; second – quark or gluon loses part of its energy during hadronization on the plasma surface. The value of enhancement depends on the details of the model, however, one can not change it significantly within reasonable models.

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